

TITLE OF THE INVENTION

SHEET-TYPE REGENERATIVE HEAT EXCHANGER AND  
MANUFACTURING METHOD THEREOF, AND REGENERATOR  
AND REFRIGERATOR USING THE SAME

BACKGROUND OF THE INVENTION

The present invention relates to a sheet-type regenerative heat exchanger used in refrigerators suitable for cryogenic cooling, manufacturing method thereof, and a regenerator and refrigerator using the same.

More specifically, the present invention relates to a manufacturing method and a structure of a regenerative heat exchanger used in various refrigeration cycles including Stirling, Gifford-McMahon (G-M), pulse-tube, Solvay, Vuilleumier, and any combination of these cycles, of regenerative cryocoolers suitable for attaining extremely low temperatures from 160 K (minus 233 °C) to 2 K (approx. minus 271 °C), in which a working fluid such as helium, hydrogen, nitrogen, argon, air, and hydrocarbon, either alone or mixed (hereinafter referred to simply as "gas") is used to make heat exchange at temperatures ranging from a normal level to a cryogenic level. The invention further relates to a regenerator, and a refrigerator using the regenerative heat exchanger.

PRIOR ART

A conventional heat storing material used in a refrigerator for cryogenic cooling is composed of a

material having large specific heat per volume in the range of temperatures at which the material is used, and is formed in various shapes such as wire mesh, chips, powder, and balls. Bronze, stainless steel, or lead-antimony alloy is commonly used for a range of temperatures from 300 K to 20 K, in the form of metal mesh ranging in mesh size from several tens to several hundreds or in the form of balls having a diameter of 50 to 800  $\mu\text{m}$ . For a cryogenic temperature from 20 K to the He superfluidity range, Pb, Pb-Sb, Nd,  $\text{Er}_3\text{Ni}$ ,  $\text{HoCu}_2$ , or  $\text{GdAlO}_3$  (GAP) is used as the heat storing material, in the form of balls, chips, or powder particles. Several tens to several hundreds grams of these heat storing material are densely packed in a cylinder to constitute a regenerator for a small refrigerator. Thermal efficiency of such structure is more than 98.5%, which is fairly high. Nevertheless, the conventional structure of the heat storing material, wherein numerous small grains of various shapes such as metal mesh, chips, powder, and balls (hereinafter referred generally to "granules") are densely packed, have various problems as described below.

In a typical regenerator of a refrigerator for achieving 10 K temperature range, different materials are packed in a stepwise fashion with filters to prevent mixing of the different materials. Specifically, balls or chips of bronze or stainless steel are used for the temperature range of from a normal level to 50 K, and those of lead alloy or  $\text{Er}_3\text{Ni}$  are used for temperatures

lower than that. However, the working fluid such as He gas (hereinafter referred to as "fluid") reciprocates within the regenerator at velocities from zero to a high level. For example, the gas flows to and from at velocities of 0 to 10-20 meters per second in operation at frequency of 60 Hz. Since at least three filters are necessary to use balls or chips of different materials such as lead alloy or  $\text{Er}_3\text{Ni}$ , the pressure loss caused by the filters is quite large. The filters can cause an input (power) loss of 5-7% at several Hz and, the loss reaches more than 10% at 60 Hz even with an optimized design of the regenerator.

The fluid, which reciprocates within the regenerator at the velocity of zero to 10-20 meters per second, collides with the balls or chips of the heat storing materials to move them, causing friction therebetween, whereby pulverized fine particles are generated. These pulverized fine particles can fill up the fluid passage between the balls or chips, or pass through the filters and contaminate the interior of the refrigerator, resulting in degradation of performance of the regenerator itself. Contamination of another part such as a cold head, which contributes to heat transfer in the refrigerator, may induce deterioration of the refrigerating output.

Furthermore, in the prior art regenerator, since specified amounts of balls or chips of lead alloy or  $\text{Er}_3\text{Ni}$  are packed with filters for separating them, the manufacturing cost becomes high and the performance of

resultant products is apt to vary.

As described above, the granules are seemingly retained under pressure by the filters. However, they are mechanically shaken or displaced because of the gas flowing within the regenerator at the speed which change from zero to a maximum level twice in one cycle. As a result, the granules are abraded by friction during a long time use so as to produce pulverized fine particles which may fill up the gaps between the granules or clog piping passages, thereby increasing the pressure loss. The pulverized fine particles may also adhere to the inner wall of a cold head, decreasing the heat transfer effect, and deteriorating the refrigerating performance.

Granules packed in the prior art regenerator have a mean particle size ranging from 40 to 800  $\mu\text{m}$ . The particle size of granules for those employing a gas having a low molecular weight such as  $\text{H}_2$  or He is approx. 100 to 300  $\mu\text{m}$ , and for a large refrigerator or a liquefier or for those employing a gas such as hydrocarbon,  $\text{N}_2$ , air, argon, or a mixed gas, the particle size of granules is approx. 300 to 800  $\mu\text{m}$ .

Uniform packing of granular heat storage materials with filters into a regenerator is hardly achievable, so that the performance of mass-produced regenerators is apt to vary. Density of the granules also varies in the regenerator, because the gas flows back and forth at the speed intermittently and quickly changing as mentioned above, and modes of operation of the refrigerator also

change. This affects the refrigerating performance.

Additionally, a secular change in the performance is naturally caused. Moreover, after disposal of the regenerator, heat storing materials made of lead or zinc can cause serious pollution to the environment. Particularly in an application of the refrigerator for an earth satellite, it is assumed that the performance deterioration of the regenerator, resulting from mechanical vibration and abrasion of the spherical heat storing materials caused by the varying gas pressure as mentioned above, can rapidly occur because there is an extremely low gravity.

To overcome the problem, some expensive regenerators use granules of a mean particle size of approx.  $250\text{ }\mu\text{m}$  with diameter errors of approx.  $\pm 10\%$ . On the other hand, the numerous granules should be densely packed as uniformly as possible in order to prevent performance deterioration, and therefore it is desirable that these granules have high sphericity and precise diameters.

Unlike steel balls for mass-produced mini-ball bearings, such requirements are hardly achievable, because such granular heat storing materials are horrendously expensive, causing the price of the refrigerator to be much higher in several to tens of order.

Another known regenerator for achieving 4 K has a multilayer structure with various different heat storing materials. For example, it may be composed of layers of bronze and stainless steel mesh having a mesh size of

several hundreds laminated in several hundreds layers, a first filter, a layer of Pb-Zn granules, a second filter, a layer of  $\text{Er}_3\text{Ni}$  granules, a third filter, a layer of  $\text{HoCu}_2$  granules, a fourth filter, a layer of GAP granules, and a fifth filter. This structure is designed for a maximum specific heat effect achieved by Pb-Zn alloy and other magnetic heat storing materials in the range of temperatures employed, and also for the prevention of the various kinds of granules from mixing with each other, or from flowing outside of the regenerator. However, the loss of refrigerating output caused by the pressure loss due to the multiple layers of filters becomes extremely large.

#### SUMMARY OF THE INVENTION

The present invention has been devised to solve the above-described problems in the prior art and it is an object of the invention to provide a long-lasting, highly efficient sheet-type regenerative heat exchanger with low pressure loss, the manufacturing method of the same, and a regenerator and refrigerator using the same.

The present invention provides a sheet-type regenerative heat exchanger, comprising: a thin, elongated sheet-like holding base coated with an adhesive on one surface or both surfaces thereof; and numerous granules such as balls, chips and fine particles having a relatively uniform particle size, which are made of one or a plurality of heat storing materials, continuously bonded

on one surface or both surfaces of the sheet-like holding base along its length over a range of predetermined width to form at least one layer.

The present invention also provides a sheet-type regenerative heat exchanger, obtained through the steps of: providing an alignment substrate formed with numerous, precisely aligned small apertures; placing numerous granules such as balls, chips, and fine particles having a relatively uniform particle diameter or size, which are made of one or a plurality of heat storing materials, into the small apertures such that each piece of the balls, chips, or fine particles is received in each one of the small apertures in the alignment substrate; and bonding the balls, chips, or fine particles onto one or both surfaces of a very thin, elongated sheet-like holding base such as a cloth or film having an adhesive layer on one or both surfaces thereof over a predetermined widthwise range along the length thereof. Further, the present invention also provides a sheet-type regenerative heat exchanger, obtained through the foregoing steps; in which numerous minute holes having a diameter less than a half of the particle diameter or size of the balls, chips, or fine particles are drilled in the sheet-like holding base at intermediate positions between adjacent small apertures formed in the alignment substrate by minute hole drilling means such as a laser electron beam, during the aforementioned bonding step. The present invention also provides a method for manufacturing the above-described

sheet-type regenerative heat exchanger, and a regenerator including the above-described sheet-type regenerative heat exchanger wound in multiple layers around a core consisting of either one piece or divided pieces, which is formed in either a columnar shape or other shapes, and formed of a material having an extremely low expansion coefficient and thermal conductivity. The present invention further provides a refrigerator including such regenerator.

According to the invention, the heat storing material such as bronze, stainless steel, Fe-Ni alloy, Pb alloy, Cu or the like is used as cores and plated with Pb or an alloy thereof to form small balls, and Nd, DyNi<sub>2</sub>, Er<sub>3</sub>Ni, and Er<sub>3</sub>Ni<sub>2</sub>Sn or the like is used to form small balls, chips or fine powder particles. These granular particles are sifted to get uniform particle size distribution. And then, they are fixedly bonded onto a very thin sheet of film, cloth, or paper (hereinafter referred to as "sheet-like holding base") which is several tens  $\mu$ m in thickness, and is coated with an adhesive, which does not shrink or become brittle even at extremely low temperatures, on its one or both surfaces, so as not to be displaced by the pressure of working gas.

Thereby, the amount of the heat storing material to be accommodated within a regenerator can be determined by the length of the sheet. Packing of heat storing material is done in a short period of time, decreasing the cost. Therefore, the present invention provides an inexpensive



regenerative heat exchanger and a regenerator having advantages of uniform and less degraded performance.

For the sheet-like holding base, a thin sheet having thickness of 10 to 100  $\mu\text{m}$  is used which comprises any one of 1) polymeric film such as polypropylene, polyethylene, capton, and nylon 6, 2) thin woven cloth made of artificial fiber such as polyethylene fiber, polyimide fiber, polyester fiber, and Kevlar<sup>TM</sup> fiber, or ceramics fiber and 3) non-woven cloth or paper made of artificial fiber or natural substance, and is coated with a synthetic resin adhesive (such as silicone resins, polyurethane resins, epoxy resins) after undergoing a primer treatment as required, on its one surface or both surfaces (with a covering tape).

In order to prevent temperature difference from being produced in a crosswise direction of the sheet-type regenerative heat exchanger coiled in multiple layers, i.e., in a radial direction of the regenerator formed in a cylindrical shape, numerous minute holes having a diameter less than a half of diameter of the granules may be drilled in the sheet-like holding base by minute hole drilling means such as a laser electron beam, before or after bonding the aligned balls or fine particles onto the holding base. Thereby, the working gas can flow through the drilled holes from one layer to another. The position and the size of such minute holes can readily be calculated by a computer based on the position and the size of the balls or fine particles.

The regenerator is constituted by the sheet-type regenerative heat exchanger wound around a core. The core is made of a synthetic resin such as Bakelite™, Teflon™ or the like having low thermal conductivity and little outgassing. Alternatively, the sheet-type regenerative heat exchanger of the invention may be wound around a pulse tube for a pulse-tube refrigerator or around an expansion cylinder for a Stirling refrigerator. If the regenerator has a diameter equal to or less than 25 mm, it is rather difficult to wind the sheet-type regenerative heat exchanger especially at the inner end, i.e., at the start of winding, because of the balls abutting against each other. That is because the distance between adjacent balls turns wider on the outer surface of the sheet while it turns narrower on its inner surface. Therefore, the diameter or size of the balls or fine particles may be differed as required from one surface to the other surface of the sheet. If the sheet has balls on only one surface thereof, it can be readily wound with its flat surface being the inner side. Alternatively, the distribution density of the balls or fine particles may be varied from one surface to the other surface of the sheet to facilitate the winding.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective diagram showing one example of a sheet-type regenerative heat exchanger according to the present invention;

Fig. 2 is a diagram showing a first embodiment of a manufacturing process of the sheet-type regenerative heat exchanger of the present invention;

Fig. 3 is a diagram showing a table of Fig. 2 on which balls are aligned in matrix;

Fig. 4 is a diagram showing a second embodiment of a manufacturing process of the sheet-type regenerative heat exchanger of the present invention;

Fig. 5 is a top plan view showing one example of an alignment substrate used in the invention;

Fig. 6 is a cross-sectional diagram showing the alignment substrate in which each ball is received in each small aperture;

Fig. 7 is a cross-sectional diagram showing one example of a sheet-type regenerative heat exchanger formed through the process according to the first embodiment of the invention;

Fig. 8 is a cross-sectional diagram showing another example of a sheet-type regenerative heat exchanger formed through the process according to the first embodiment of the invention;

Fig. 9 is a diagram showing a state wherein the sheet-type regenerative heat exchanger shown in Fig. 8 is stacked in multiple layers;

Fig. 10 is a cross-sectional diagram showing one example of a sheet-type regenerative heat exchanger formed through the process according to the second embodiment of the invention; and

Fig. 11 is a diagram showing a state wherein the sheet-type regenerative heat exchanger shown in Fig. 10 is stacked in multiple layers.

#### DESCRIPTION OF THE PREFERRED EMBODIMENT

Fig. 1 is a perspective diagram showing part of a sheet-type regenerative heat exchanger according to the present invention. A sheet-like holding base 4 carrying granules (small balls) 3 stuck on both faces thereof is wrapped around a columnar core comprising four divided pieces 11-1, 11-2, 11-3, and 11-4. The sheet-like holding base 4 is wound into a coil in multiple layers to constitute a regenerator. The working gas flows in the axial direction of the columnar core.

Fig. 2 is a diagram showing a first embodiment of the manufacturing process of the sheet-type regenerative heat exchanger according to the present invention. Reference numeral 1 represents a table having extremely high flatness, reference numerals 2-a and 2-b represent an end frame and a position control sensor, respectively. Numeral 3 represents the small balls. Numerals 4 and 4-1 respectively denote the sheet-like holding base, and one end of the sheet-like holding base. Reference numerals 5 and 6 denote covering tapes. Reference numerals 7, 8, 9, and 10 respectively denote a winding frame, a guide roller, a rotary take-up device, and a roller.

Fig. 3 is a diagram showing the table 1 of Fig. 2 having a flat surface to a high degree of precision, on

which the small balls 3 are arranged in a matrix thereon.

In Fig. 2, a large number of balls 3 with a mean diameter of 250  $\mu\text{m}$ , for example, made of a Pb-Sb alloy are randomly arranged within the frame 2 (having dimensions of 50 mm inner width and 2000 mm inner length, for instance) to form one layer of the balls (so as not to be superposed upon one another). One end 4-1 of the sheet-like holding base 4, which is composed of a very thin, approx. 30  $\mu\text{m}$  thick cloth of ceramic fiber impregnated with an adhesive made of metamorphic silicon or epoxy resin through a primer, has the covering tapes 5, 6 attached on both faces thereof, and is wound around the winding frame 7, is fixed to the end frame 2-a. The roller 10, which has a soft pressing surface and is equipped with has a position control sensor 2b for finely controlling the thickness of bonding in accordance with the diameter of the metal balls 3 so as to be 15  $\mu\text{m}$ , for example, and the winding frame 7 are rotated to move towards the direction X1, X2 to the right side of Fig. 2, while respectively applying adequate forces a and b to the sheet-like holding base 4.

The forces a, b applied to the sheet-like holding base 4 through the roller 10 and the winding frame 7, as well as the rotation speed of the roller 10 and the winding frame 7 vary in accordance with the diameter of the sheet-like holding base 4 coiled around the winding frame 7. These are appropriately controlled with a computer based on data fed from the position control sensor and other sensors. The guide roller 8 is moved

toward the direction of X3 while applying an adequate force c to the covering tape 5. The force c and the rotation speed of the guide roller 8 are controlled similarly to the roller 10 and the winding frame 7. Rotation of the rotary take-up device 9 is likewise controlled. The arrows in Fig. 2 denote either the direction of force or the direction of movement of various members. A sheet-type regenerative heat exchanger having balls only on one face thereof is obtained through the process described above.

At intermediate positions between adjacent granules such as balls, chips and fine particles, a large number of minute holes having a diameter equal to or less than half of the mean particle diameter or the size of the balls, chips, or fine particles may be formed in the sheet-like holding base 4 for providing gas passage holes. This may be achieved by a laser electron beam or any other minute hole drilling means (not shown) either immediately before or after the pressure application by the roller 10.

Fig. 4 is a diagram showing a second embodiment of the manufacturing process of the sheet-type regenerative heat exchanger according to the present invention. Reference numerals 3 and 11 respectively represent small balls and an alignment substrate. Other reference numerals indicate the same elements as those of Fig. 2. Fig. 5 is a top plan view showing one example of the alignment substrate used in the invention. The alignment substrate 11 has small apertures 12 which may be through

holes or dimples. Reference numeral 13 denotes intermediate portion between adjacent small apertures.

In Fig. 5, the alignment substrate 11 has a width of approx. 5 cm to 25.4 cm from an ordinary temperature end 14 to a low temperature end 15 in its widthwise direction, and the gas flows in the direction of Y. The length of the alignment substrate 11 is approx. 100 cm to several hundreds cm, which varies depending on the refrigerating output, shape and size of the regenerator, and the range of the temperature applied. The numerous small apertures 12 (through dimples) have a diameter of approx. 50% to 80% of the diameter or size of the small balls, chips, or fine particles. The diameter of the small apertures may be suitably set so that a single small ball, chip or fine particle is not buried deep in a small aperture, but is retained therein when adhering the sheet-like holding base thereto. To be specific, for lead alloy balls having 200  $\mu\text{m}$  diameter, the small apertures should preferably have 100 to 160  $\mu\text{m}$  diameter. In practical applications, it was ascertained that around 140  $\mu\text{m}$  was most preferable.

In Fig. 4, the granules such as small balls, chips and fine particles are arranged on the alignment substrate 11, which has been preliminarily formed with a matrix of small apertures arranged precisely by computer control, so that each piece of the granules is received in each one of the small apertures in the alignment substrate 11, and the alignment substrate with the granules is set on the table via the end frame. Thereafter, through the process steps

similar to those described above with reference to Fig. 2, the sheet-like holding base is adhered to the balls, chips, or fine particles. As mentioned above, a large number of gas passage holes having a diameter equal to or less than half of the particle diameter or the size of the granules may be drilled in the sheet-like holding base 4, at intermediate positions between adjacent granules, by a laser electron beam or any other small hole drilling means (not shown) either immediately before or after the pressure application by the roller 10.

Fig. 6 is a cross-sectional diagram showing the alignment substrate 11 in which each piece of the small balls is received in each one of the small apertures. Reference numeral 11 denotes the alignment substrate. Reference numerals 3 and 3-1 respectively denote the small balls, and part of the small balls fitted in through the small apertures of the alignment substrate 11. The alignment substrate 11 may be made of any of metal, synthetic resin, ceramics, and other materials which can withstand the pressure applied by the roller 10 through the sheet-like holding base 4. The thickness of the alignment substrate 11 may be suitably selected within the permissible range of operativity.

Fig. 7 is a cross-sectional diagram showing one example of the sheet-type regenerative heat exchanger according to the first embodiment of the invention described above. Reference numerals 3, 4, and 4-2 respectively represent the small balls, the sheet-like



holding base, and the adhesive layer. In the example shown in Fig. 7, the small balls 3 are bonded to only one face of the sheet-like holding base 4. Fig. 8 is a cross-sectional diagram showing another example of the sheet-type regenerative heat exchanger according to the first embodiment of the invention described above. Reference numeral 4-3 represents the adhesive layer provided on another face. In the example shown in Fig. 8, the small balls 3 are bonded to both the adhesive layers 4-2 and 4-3 formed on one face and the other face of the sheet-like holding base 4. Fig. 9 shows a state wherein the sheet-type regenerative heat exchanger shown in Fig. 8 is stacked in multiple layers.

To stick the small balls on both surfaces of the sheet-like holding base, a large number of the small balls 3 made of a Pb-Sb alloy with a diameter of 250  $\mu\text{m}$  are arranged again on the table 1 within the frame 2 as described above. And then, a sheet-like holding base 4 having small balls 3 already bonded on its one surface through the above described process is put on the table with the surface having small balls 3 upward; to be pressed against the balls 3 on the table 1 while the covering tape 6 is peeled away from the other surface of the sheet-like holding base, so that the balls 3 adhere to the sheet-like holding base. The sheet-type regenerative heat exchanger according to the invention has been described as having approx. 2000 mm length in the foregoing. It should be noted, however, that the above-

described manufacturing process can readily be applied to an automatic system for continuously manufacturing a several tens meters sheet-type regenerative heat exchanger.

With regard to the small balls 3 for the heat exchanger to produce a temperature as low as 15K, it is preferable to use different types of the small balls. For example, three types of the small balls are bonded on a sheet-like holding base having 150 mm width (length may be set as desired), so as to arrange bronze balls, stainless balls and Pb, Nd or Er<sub>3</sub>Ni balls respectively in an area defined between an ordinary temperature zone at one widthwise end of the holding base and a 120K zone at about 50 mm from the end, and area defined between the 120K zone and a 40K zone at about 100 mm from the end, and an area defined between the 40K zone and a less than 20K zone at 150 mm from the end i.e. the opposite end. These balls are sifted to have the same particle size or diameter, but there still remains a discrepancy of approx. several %.

Such heat exchanger containing different types of heat storing materials can be fabricated as follows. Thin wires 20  $\mu$ m in diameter of Teflon™ or Kevlar™ are strung along the length of the frame 2 between holes provided in its end frame 2-a and an end frame 2-c (not shown) on the opposite side. Both end frames are provided with vertical position alignment mechanisms in combination with the position control sensor 2-b. The wires are stretched over the table at a height which is approximately a half of the diameter of the balls 3. Thus the frame is divided

widthwise into several partitions along its length, in each of which a different type of heat storage material may be placed in matrix, so that the different types of balls are bonded on lengthwise areas divided widthwise of the holding base. The thin wires may be removed after the completion of the sheet-type regenerative heat exchanger, or left as they are, since they have virtually no effect on the performance of the sheet-type regenerative heat exchanger in respect of pressure and heat.

Fig. 10 is a cross-sectional diagram showing one example of a sheet-type regenerative heat exchanger obtained through the second embodiment. Reference numerals 3 and 4 respectively represent the balls and sheet-like holding base, and 4-2 and 4-3 represent the adhesive layers. As shown in Fig. 10, the balls 3 are bonded to both adhesive layers 4-2, 4-3 on one and the other surfaces of the sheet-like holding base 4.

Fig. 11 shows a state wherein the sheet-like holding base shown in Fig. 10 is stacked in multiple layers.

This sheet-type regenerative heat exchanger having balls 3 on both surfaces thereof is assembled into a regenerator as shown in Fig. 1. Bakelite<sup>TM</sup> or the like having low thermal conductivity is used for a columnar core, which may be divided into two or several parts. In the illustrated example, the core has four divided parts 11-1, 11-2, 11-3, and 11-4. A predetermined length of the sheet-type regenerative heat exchanger having a large number of balls 3 on both sides thereof is wound around

the core. The coil of sheet-type regenerative heat exchanger is then inserted into a cylindrical case to complete the regenerator. The core should not necessarily be divided but may be one piece. The number of divided parts of the core is not limited to that in the examples given above, and the divided parts of the core may have various different shapes.

### Comparison Test 1

A comparison was made on a testing refrigerator, with respect to the refrigerating output between a regenerator of the invention using the sheet-type regenerative heat exchanger having a large number of balls 3 on both surfaces of a sheet according to the invention, and a conventional regenerator including a large number of laminated metal meshes and lead balls.

### Regenerator of the Invention

A sheet-type regenerative heat exchanger was prepared to have, on both surfaces thereof, bronze and stainless steel 316L balls having a mean particle diameter of  $250\ \mu\text{m} \pm 5\%$  over the lengthwise area of a sheet-like holding base from its ordinary temperature end to the position 100 mm spaced from the end, and Pb-Sb balls having a mean particle diameter of  $250\ \mu\text{m} \pm 5\%$  over the lengthwise area from the position 100 mm spaced from the end to the position 150 mm spaced from the end. The sheet-type regenerative heat exchanger was wound around a

four-piece columnar core 4 mm in diameter and 150 mm in length made of Bakelite™, which is then inserted into a thin cylinder of stainless steel having an inner diameter of 20 mm, to constitute a regenerator of the invention.

#### Conventional Regenerator

Approx. 900 disks with a diameter of 20 mm of stainless steel (304) mesh having a mesh size of 350 were packed to a depth of 100 mm in a thin cylinder of stainless steel with an inner diameter of 20 mm. Then, a large number of Pb-Sb balls having a mean particle diameter of  $250\text{ }\mu\text{m} \pm 5\%$ , sandwiched between two felt sheets for retaining the balls in position were packed to an additional depth of 50 mm in the thin cylinder to complete a regenerator. Incidentally, each of the felt sheets includes a sheet of size 400 stainless steel mesh and has a thickness of 4 mm.

#### Testing Refrigerator (GM-type Pulse-tube Refrigerator)

##### Operation Conditions A

Compressor input: 1.2 - 2 kW

Working gas pressure: 1.5 MPa

Working gas: He

Pulse tube: 8 mm in diameter, 160 mm in length

Pulse tube operation frequency: 3 Hz

#### Test Results: Refrigerating Output

Regenerator of the invention: 2W at 20K

Conventional regenerator: 1.6W at 20K

### Comparison Test 2

Next, the length of the regenerator and heat storing materials used therein were increased, compared with those in the comparison test 1 to make a comparison between a regenerator of the present invention and a conventional invention.

### Regenerator of the Invention

The length of the regenerators was increased by 80 mm as compared to the specimen in the first comparison test so as to be 230 mm while the inner diameter was kept 20 mm. For the generator of the invention,  $\text{Er}_3\text{Ni}$  balls having a mean particle diameter of  $250\text{ }\mu\text{m} \pm 5\%$  were bonded to both sides of an 80 mm wide sheet-like holding base to obtain a sheet-type regenerative heat exchanger which was wound around a four-piece columnar core of Bakelite™, and additionally inserted into a thin cylinder of stainless steel having an inner diameter of 20 mm and an additional length of 80 mm to construct a regenerator of the invention for the test 2.

### Conventional Regenerator

$\text{Er}_3\text{Ni}$  balls having a mean particle diameter of  $250\text{ }\mu\text{m} \pm 5\%$  were additionally packed in the increased 80 mm portion of the thin cylinder, together with one more felt sheet for retaining the balls.

## Testing Refrigerator (GM-type Pulse-tube Refrigerator)

### Operation Conditions B

Compressor input: 2.5 - 4 kW

Working gas pressure: 0.8 - 1.5 MPa

Working gas: He

Pulse tube: 6 mm in diameter, 240 mm in length

Pulse tube operation frequency: approx. 1 Hz

### Test Results: Refrigerating Output

Regenerator of the invention: approx. 180 mW at 4.2K

Conventional regenerator: approx. 120 mW at 4.2K

In conducting the above-described comparison tests, the radiation shields for covering a portion between an ordinary temperature end and position 100 mm spaced from the ordinary temperature end of the regenerator, and the cold head were cooled by another small-type pulse-tube refrigerator, in order to remove the factors of thermal conduction losses and thermal radiation.

From the results of the above-described tests, it was ascertained that the refrigerating output of the refrigerator using the sheet-type regenerative heat exchanger of the invention was improved by approx. 25% in the region of 20K, and by approx. 50% in the region of 4.2K.

It should be noted that the sheet-like regenerative heat exchanger of the present invention can also be

applied to other types of regenerative cryocoolers such as Stirling refrigerator and GM-cycle refrigerator to achieve the same effects.

In the regenerator of the invention, the flow resistance was reduced by approx. 20%, while the refrigerating efficiency was increased by 10% or more, as compared to a conventional regenerator. This is because the construction of the regenerator according to the invention allowed the working gas to flow more smoothly as compared to a case in which balls are densely packed, as well as a good energy storage effect of the regenerator was obtained, which all led to favorable overall performance.

The present invention offers the following advantages:

a. It is no more necessary to employ a filter made of a high density fiber such as flannel, felt, gauze, lint, metal mesh, or sintered metal, for retaining the balls in the regenerator, which is essential in the prior art.

b. The pressure loss caused by the filter is eliminated, leading to an improvement in the refrigerating output at least by 25% in the cryogenic temperature region of 20K. The production time of a regenerator is also reduced to approx. 1/10, whereby an inexpensive, highly efficient regenerator can be provided.

c. In an conventional regenerator, each of filters arranged at both upper and lower ends occupies 4 mm space in the total length, 50 mm for example, in the regenerator



of the present invention, the heat storing materials can be packed more, by the volume of the filters, than the conventional type since the filters are not necessary. As a result, the share of heat storing per unit volume is decreased, and the heat storing capacity is increased in the regenerator of the invention. Accordingly, there is less volume of dead space, whereby, in combination with the decrease in the pressure loss, the refrigerating output is improved.

d. Any heat storage material having a substantially uniform particle size can be retained on the sheet-like holding base to make a regenerative heat exchanger.

e. The structure wherein numerous fine particles of heat storing materials are retained on a sheet makes various applications of the regenerator possible. For example, the high efficiency of the regenerator will not be affected even if it is installed horizontally, or subjected to an extremely large degree of acceleration or severe vibration. Thus the regenerator will find applications for the refrigerators mounted on an earth satellite or on a superconducting magnet floating train.

f. The heat storage material which may cause environmental pollution such as lead can readily be recovered after disposal of the regenerator, as it is bonded to a sheet.

g. Accordingly, a refrigerator using a sheet-type regenerative heat exchanger of the present invention has improved reliability in respect of its performance.